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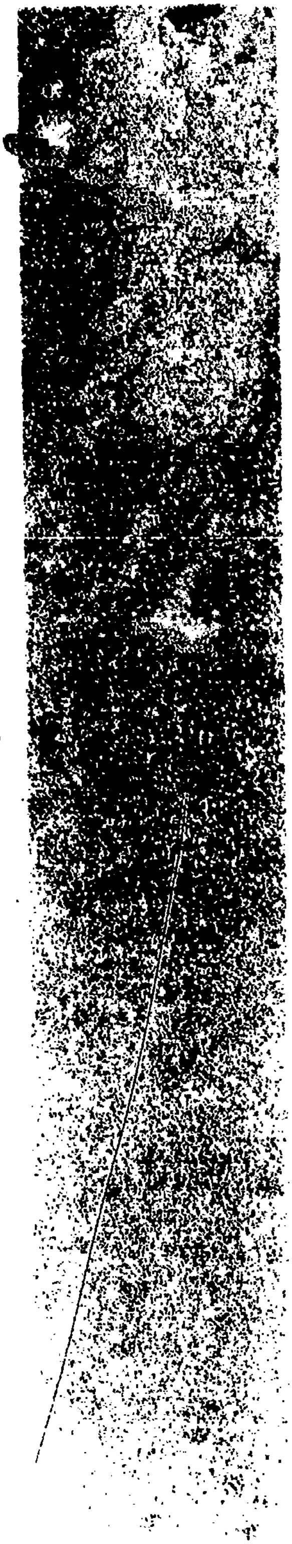
ABSTRACT

Suggested are methods for the collection of field evidence about processes that form plutonic and metamorphic rock. Description and discussion of these types of rocks are provided. The planning and execution of a successful field trip is discussed. Advanced field projects are also discussed. Included are five appendices, references, and a glossary. (RE)

field guide to PLUTONIC and METAMORPHIC ROCKS

William D. Romey



Plutonic and metamorphic rocks appear in many areas at the earth's surface. Samples from deep drill holes show that these rocks underlie the layered rocks that cover most land. Often they are beautiful rocks, containing interesting structures, unusual minerals, and, occasionally, large, well-formed crystals. Yet nowhere has man been able to observe these rocks in the process of formation. Field evidence and experiments lead geologists to believe that plutonic and metamorphic rocks form deep below the surface, where temperatures and pressures are high. Looking for field evidence about processes that form these rocks is the subject of this pamphlet.

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FIELD GUIDE TO

Plutonic and Metamorphic Rocks

William D. Romey

Series Editor: Robert E. Boyer

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Plutonic and Metamorphic Rocks

INTRODUCTION

All of the many kinds of rocks at the earth's surface contain clues that can help you determine something about how they formed. It is easy to imagine that a piece of sandstone, for example, formed when grains of sand were cemented or squeezed together, perhaps like a snowball. You may readily conclude that rocks on the sides of a volcano formed when lava spewed out from a crater, cooled, and became solid, preserving flow markings like those in the sauce on a hot-fudge sundae.

Other kinds of rocks, however, called plutonic and metamorphic rocks, cannot be seen forming at the surface of the earth, even though we can find them there now. These rocks are generally exposed in mountain ranges, or in what are thought to be the roots of ancient mountain ranges. For these reasons, and from laboratory evidence, both plutonic and metamorphic rocks are believed to have formed deep below the earth's surface. How did these rocks become exposed to view? During mountain building, the crustal layers must have been gradually uplifted, and weathering and erosion must have slowly stripped away the upper cover of rocks.

Figure 1. Granite. (A) Outcrop. (B) Close-up of outcrop. (C) Thin slice seen under a microscope (cross-polarized light).

When the materials that make up sandstone, limestone, and other sedimentary rocks that accumulate at the earth's surface are buried deeply under other rock layers, they are subjected to high temperatures and pressures. These changes in conditions cause minerals in the rock mass to react chemically. If the rock is not actually melted, the resulting rocks, such as schist, gneiss, and marble, are *metamorphic rocks*. They commonly show a pattern or orientation in the arrangement of their grains, like the sedimentary rocks from which they formed. Pore spaces that existed between grains of the original sedimentary rocks disappear as the grains are squeezed together and chemical reactions take place.

If sedimentary or metamorphic rocks are buried still deeper, they may become so hot that they melt, forming *magma*. Later cooling of the magma, perhaps several kilometers below the surface, produces *igneous* (fire-formed) *rocks*.

When you look at a rock, however, it may not be possible to tell how it formed. Rock that has been heated almost to the melting point is often indistinguishable from rock containing the same minerals that has actually been melted. Geologists lump these kinds of rock into a category called *plutonic*

rocks (from Pluto, the Roman god of the underworld). A sample of a plutonic rock, such as granite, is probably igneous in origin, but it may be metamorphic. However, a metamorphic plutonic rock looks more like other plutonic rocks than like a metamorphic rock. Plutonic rocks tend to have large grains with little or no pattern or orientation. Table 1 gives a summary of the characteristics of the different classes of rocks.

Table 1. Characteristics of Rock Types

Rock Type	Pore Spaces	Orientation of Grains
Sedimentary	yes	yes
Metamorphic	no	yes
Plutonic	no	little or none

Laboratory work and field evidence about the structure and appearance of large plutonic rock bodies are the basis for arguing whether they formed from magma or by metamorphism that stopped short of melting. This field guide is intended to help you learn to observe plutonic and metamorphic rocks and to find clues as to how they formed. In turn, you will also learn something about what must be happening below the earth's surface even today.

PLUTONIC ROCKS

Plutonic rocks commonly occur in large, blob-shaped masses called *plutons* that may range in surface area from a few square meters to many tens or even hundreds of square kilometers, and may extend several kilometers below the surface. The rocks in plutons are usually massive and contain mineral grains large enough to be seen readily with the naked eye (Figure 1). Mineral grains characteristically grow together in an interlocking fashion called *crystalline texture* (Figures 1B and 1C). Some plutonic rocks have crude layering; others have mineral grains arranged vaguely parallel to each other suggesting that these grains floated in magma—much as logs float in a sluggish stream.

Plutonic rocks commonly contain the same kinds and amounts of minerals found in many lava flows. Quartz, feldspar, and a few dark-colored minerals, in various proportions, are the main minerals in plutonic rocks. (See Appendix I.) Gradations found in some places between lava flows and plutonic rocks lead field workers to conclude that plutons formed from melted rock that crystallized below the surface. The central parts of some thick lava flows have the same mineral content and texture as some plutonic rocks. Rocks in the root zones of deeply eroded volcanoes look much like plutonic rocks from within the crust.

In many places, bodies of plutonic rock that are large in surface area, but relatively thin like a table top, cut across the layering and structure of other rocks (Figure 2). The layers must have been there first, and the plutonic rock moved in, or intruded, later. Such cross-cutting plutonic rocks are therefore younger than the rocks they intrude.

Granite is the most abundant plutonic rock exposed at the earth's surface. Although granite bodies cover extensive areas on the continents, estimates of rock densities from measurements of the earth's gravitational attraction suggest that most granite bodies are relatively shallow, probably extending downward only a few kilometers or, at most, a few tens of kilometers. The magmas from which many granites crystallized probably came from the melting of sedimentary, metamorphic, and volcanic rocks pushed downward into the root zones of newly forming mountain chains.

Some geologists believe that a few granites formed by a process called *granitization*, in which chemical components of older rocks separate, migrate, and recrystallize without actual melting to produce granite that is metamorphic in origin.

Figure 2. Intrusion of dark-colored plutonic rock cutting metamorphic rock.

Where there is no clear field and laboratory evidence that the plutonic rock formed by crystallization from a liquid, a granitization origin must be considered. Nonetheless, "granitized" granites may still be classified with the plutonic rocks, for they have indeed formed at a depth within the crust. As is true throughout nature, we must recognize many gradations among rock types and rock-forming processes. Plutonic and metamorphic rocks grade into one another, for they form in much the same environment.

METAMORPHIC ROCKS

Most metamorphic rocks look very different from plutonic rocks. One reason is that the mineral grains grow together in different ways in the two groups of rocks. Compare Figure 1, which shows a typical plutonic rock, with Figure 3, which illustrates major kinds of metamorphic rocks. In metamorphic rocks, minerals are commonly aligned parallel to each other, enabling the rock to split easily in certain directions. Layering of various kinds can be seen in most metamorphic rocks although in many these layers are crumpled and

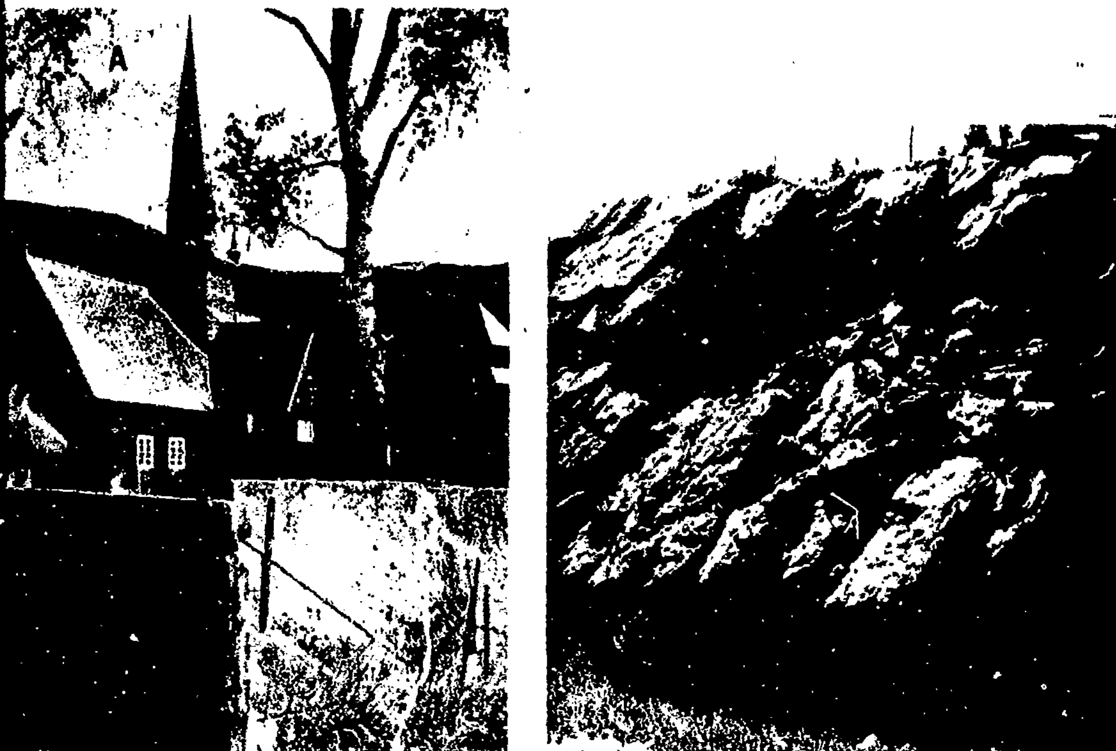


Figure 3. Metamorphic rocks. (A) Slate fence, outcrop of slate, and close-up of slate outcrop.

B

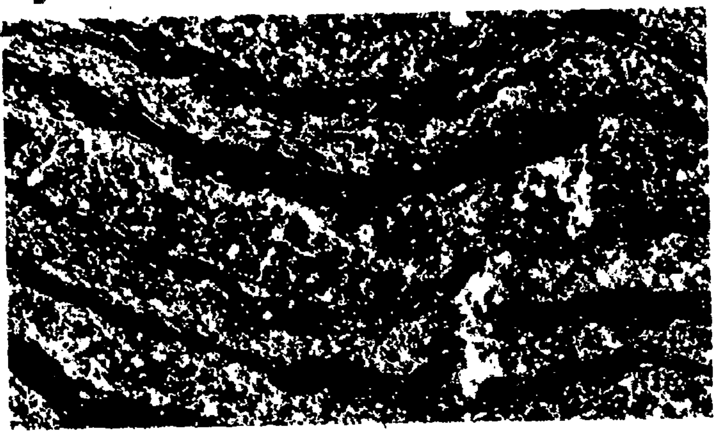
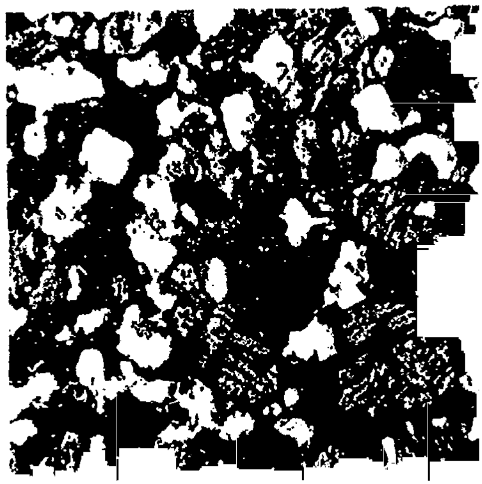


Figure 3. (B) Staurolite-mica schist (note that staurolite crystals grow as cross-shaped "twins"), and a thin slice of quartz-mica schist seen under a microscope. (C) Layered gneiss in outcrop, close-up of layers, and thin slice of one of the dark layers, seen under a microscope.



folded. Such folding may involve large rock masses and be clearly visible from a distance (Figure 4), or it may be too small to be seen except through a microscope.

Metamorphic rocks contain a greater variety of minerals than do plutonic rocks, because great heat breaks down many minerals. Whereas quartz, feldspar, and a few dark-colored minerals are the only minerals present in large quantities in most plutonic rocks, metamorphic rocks may contain many different minerals in almost any proportions. However, certain groups of minerals are commonly associated in certain kinds of metamorphic rocks, and the distinctive mineral combinations provide important clues about how these rocks formed.

The word metamorphic is taken from the Greek words *meta*, meaning change, and *morphe*, meaning form. A metamorphic rock, then, has been converted from one kind of rock into another. But how are rocks metamorphosed (changed)? Laboratory experiments reveal that when rocks are subjected to high temperature and pressure, chemical reactions may form characteristic metamorphic minerals from the minerals originally in the rock.

Figure 4. Folded rocks. (A) Folded layers weathered out. (B) Folds and pinched-out blobs seen in a road cut.

Conditions in the Earth's Interior Promote Metamorphism

Measurements made in deep mines and drill holes reveal that temperatures within the earth's upper crust increase downward at an average rate of about 30°C per kilometer. At this rate, what temperature would you expect at a depth of ten kilometers? At 20 kilometers? Below about 20 kilometers from the surface, however, the temperature evidently increases more slowly, since rocks begin to melt at temperatures greater than about 700°C, and there is no evidence to suggest that the earth is mainly molten at depths as shallow as 30 or 40 kilometers. Indeed, evidence based on the study of vibrations caused by earthquake waves indicates that at these depths the earth behaves as a solid.

Pressure also increases rapidly with depth, caused by the weight of overlying rock and the compression of water vapor and other gases trapped in its pore spaces. Imagine the weight of a column of rock one meter square and ten kilometers high! Great pressures may also be produced by the processes of mountain building, as evidenced by tight folding.

But how do sedimentary and volcanic rocks at the earth's surface get down to depths where high temperature and pressure can convert them into metamorphic rocks, or even melt them? These

rocks commonly accumulate in basins located at the edges of continents. Present geologic theories suggest that sea-floor spreading may cause these basins to be pulled slowly under the continental edge as layer upon layer of sediments is deposited. In some basins piles of sediments may become many kilometers thick. As the sediments are moved downward, the increased temperature and high pressure cause the minerals to react chemically—to be metamorphosed.

Metamorphism can also occur when magma comes into contact with other rocks, as when a lava flow pours from a volcano The kind of baking that occurs in this way is called *contact metamorphism.* It can be seen at the earth's surface where a lava flow has spread over soil or rock giving it a "baked" appearance.

"Reading" a Metamorphic Rock

All metamorphic rocks were once other rocks: sedimentary, volcanic, plutonic, or even an earlier generation of metamorphic rocks. If you look at a metamorphic rock with the right kinds of questions in mind, you may be able to tell what kind of rock it was before—its "parent" rock. The parent rock of marble is probably limestone (both are composed almost entirely of the mineral calcite), and quartzite is likely to be the "offspring" of quartz sandstone. Other examples of parent rocks and their metamorphic offspring are given in Appendix II.

For many metamorphic rocks the ancestry is more difficult to determine. Three or four possible parent rocks may have to be considered. For example, a sandstone made of grains derived from the erosion of granite may have the same chemical composition as real granite, and the metamorphic offspring of these two rock types could be identical. Furthermore, during metamorphism some atoms may move out of one mineral or rock and accumulate elsewhere to form new minerals there. If this occurred, the metamorphic rock's composition may give a wrong idea about the nature of the parent rock. In spite of these difficulties, the composition of a metamorphic rock commonly yields useful information about the rock's origin.

In the early 1900's several geologists recognized that metamorphic rocks which apparently had identical parent rocks looked very different. These geologists ground up samples of slates, phyllites, schists, and gneisses (Figure 3)—all metamorphic rocks of quite different appearance—and chemically analyzed the resulting powders. They realized that the different combinations of different minerals all had the same chemical composition as mud or clay. Why did these offspring of the same parent material look so different from each other and contain different minerals (Appendix II)? Perhaps these different metamorphic rocks had been buried to different depths. If clay or mud were buried deeper and deeper it would first be converted into shale, a sedimentary rock, then progressively into the metamorphic rocks slate, schist, and finally gneiss. With still deeper burial, it would ultimately melt and form a new plutonic igneous rock. Weathering of any of these rocks would form clay again.

Geological experimenters have since subjected clays to high temperatures and pressures under carefully controlled conditions in the laboratory. In this way they have been able to confirm and refine conclusions originally based on field work. Modern field and experimental studies have made it possible to recognize certain key groupings of minerals that allow the probable depth at which the rocks have been metamorphosed to be inferred. However, it is important to realize that actual pressures and temperatures within the earth's crust are not accurately known. Thus it is not possible to infer *accurately* the depths at which the rocks formed, although good estimates of these depths can be made.

Various groups of key minerals and the probable temperatures and pressures at which they formed, with approximate depths within the crust, are indicated in Figure 5. In the zone of low-pressure metamorphism by baking, the commonest rocks are fine-grained, flinty hornfelses. The low-grade rocks include slates, phyllites, and some schists commonly containing chlorite, epidote, and mica. The medium-grade rocks include schists, amphibolites, and some gneisses. Garnet, micas, hornblende, pyroxene, staurolite, kyanite, and sillimanite may be present in certain combinations. The high-grade metamorphic rocks include mainly coarse-grained gneisses with little or no mica or hornblende. They are characterized especially by sillimanite, garnet, and pyroxene. The highest-

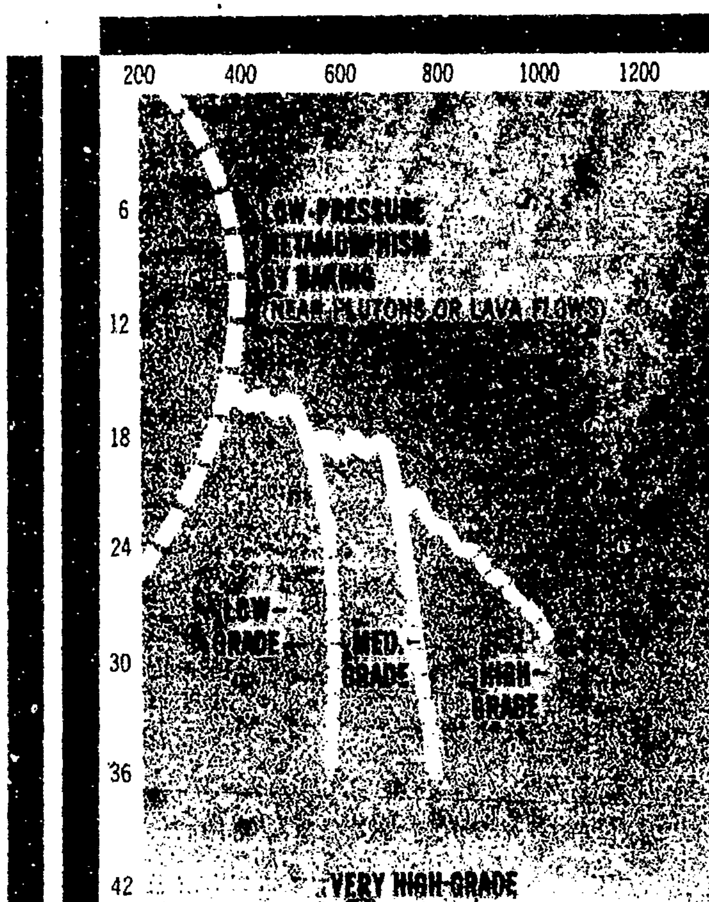


Figure 5. Diagram showing temperatures and depths of burial required to produce various grades of metamorphism. Typical rock types characteristic of the various grades are listed in Appendix IV.

grade metamorphic rocks are gneisses composed entirely of light pink garnet and deep green pyroxene. Rocks in any of the grades below the highest may also contain quartz and feldspars, depending on the overall composition of the rock.

Migmatites

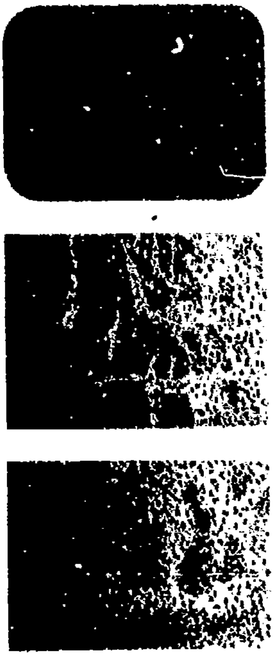
Some areas contain mixed rocks, mixtures of plutonic and metamorphic rocks called *migmatites*, like the ones shown in Figure 6. Some migmatites are metamorphic rocks that contain a few isolated patches of granite or other plutonic rock. Others are mainly plutonic, but contain blocks of metamorphic rock. Mixed rocks may have formed by partial melting of metamorphic

Figure 6. Migmatites. (A) Partially recrystallized masses of metamorphic rock in granite. (B) Rounded, boulder-like pieces of dark plutonic and metamorphic rocks in granite.

rock, by injection of granitic material formed elsewhere, or by granitization of parts of the rock. Figure 7 diagrammatically illustrates some relationships of mixed rocks you may find.

Migmatites, as well as plutonic and metamorphic rocks, are more abundant than they appear to be. Sedimentary rocks cover about three quarters of the earth's land surface. However, studies of earthquake waves and data from drill holes show that probably more than 95 percent of the earth's crust below the surface consists of metamorphic and plutonic rocks—mainly metamorphic rocks in the upper part and plutonic rocks at greater depths. Great masses of granite and other plutonic rocks may be hundreds of kilometers long and wide, like those in the Sierra Nevada and Coast Ranges of the western United States. At the edges and draped over the tops of these masses are metamorphic rocks. Commonly a zone of migmatites occurs along the contact between the plutons and the adjacent metamorphic rocks.

A



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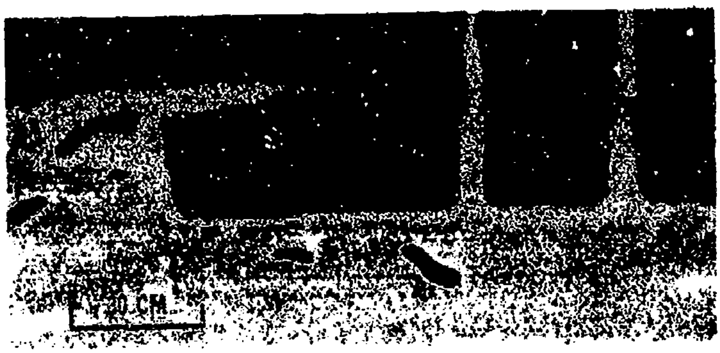


Figure 7. Structures in mixed rocks. (A) Gradations between metamorphic rocks, at the left of each diagram, and plutonic rocks at the right. (B) Intrusive relationships. The gray-colored material has probably been squeezed into the other. (C) Granitic rock (gray-colored) containing rotated blocks of layered metamorphic rock. In places, the crystals in the granite are aligned parallel to the layers in the metamorphic rock. (D) Block diagram showing a contact between layered metamorphic rock and granite.

TAKING A FIELD TRIP

Setting Your Goals

Before taking a field trip, decide what you wish to study. Certain questions should be in your mind before you begin. Here are some specific goals:

1) Determine where in your area metamorphic and plutonic rocks are found.
2) See how they differ from sedimentary rocks.
3) Make a collection of common metamorphic and plutonic rocks.
4) Collect and study metamorphic minerals.
5) Determine whether the rocks in one outcrop can be related to rocks in other outcrops.
6) Study the groups of minerals present in metamorphic rocks and make conclusions about the temperature and pressure conditions under which the rocks formed.
7) Make a simple geologic map of your area to show the surface distribution of different kinds of metamorphic and plutonic rocks.
8) Work out the sequence of events that has affected an area of metamorphic rocks.

9) Discover whether metamorphic and plutonic rocks are used as building stone in your town.

The detailed suggestions in the following sections are organized in approximate order of difficulty. Easier suggestions are listed first, and the more complicated ones are included under Advanced Field Projects. Before undertaking an advanced project, make sure that you first master the techniques suggested here.

Field Equipment

A list of suggested basic equipment for field trips follows. How much of it you will need depends on what you plan to do. The main things needed are curiosity, willingness to observe carefully, and an imagination.

Hand lens (preferably 10-power)
Small sledge hammer (2- or 3-pound head) or geology pick
Plastic glasses or goggles to protect your eyes while hammering on rocks
Small packsack for carrying samples, paper or cloth bags for the samples, and a felt marking pen
Notebook
Topographic map of the area you will visit. Such maps can usually be purchased at local bookstores, or ordered from the U.S. Geological Survey. (See References.)
Compass (necessary only if mapping is planned, or if you will be in areas away from roads where you might otherwise become lost)
Small dropper bottle containing dilute hydrochloric acid (10%), which may be obtained at drug stores (needed only in areas where marble is present)
Sturdy shoes or boots
Pencils, pen, and ruler
Camera, if available

If you go onto private property, be sure you get permission from the owner. Most people will let you onto their property if you ask them *first*.

Figure 8. Schematic geologic map of the United States showing approximate location of main areas of plutonic and metamorphic rocks.
(*Note:* Small dark areas representing plutonic rocks should also appear in the regions designated as metamorphic in Wisconsin, Minnesota, Vermont, New Hampshire, Rhode Island, Connecticut, New York, and Massachusetts. Cape Cod should not be shown as containing metamorphic rocks.)

Finding Outcrops

In parts of the United States, metamorphic and plutonic rocks are buried beneath rocks such as sandstone, limestone, shale, and volcanic rocks. Areas where you can expect to find exposures of metamorphic and plutonic rocks at the surface are shown in Figure 8. Why do you think metamorphic and plutonic rocks are so abundant in mountainous areas and so rare in the interior of the continent? More detailed information should be available on geologic maps of your local area or state, or on other available geologic maps. Some of these maps are listed in *Selected Maps and Earth Science Publications*. (See References.) Or, write directly to the state geological survey in your state capital for information on the availability of geologic maps. Geology faculty members at local colleges will suggest suitable maps if you phone or write to them.

Road cuts are one of the best places to look for fresh rock exposures. But be careful of traffic and don't knock chunks of rock onto the road! Quarries are particularly good places to observe fresh rock surfaces, but be careful of falling rocks and crumbling quarry edges. Stream valleys and rocky areas along a seacoast or lake shore are also good places to expect exposures. Hilltops may provide outcrops.

Even though there may be no outcrops of plutonic or metamorphic rocks nearby, you may find boulders of these rocks in areas in those parts of the northern United States that were covered a few thousand years ago by the Pleistocene ice sheets (Figure 8). Where do you think these boulders came from?

Visit to an Outcrop

First, locate the outcrop on your topographic map or road map. Give it a number on the map and in your notebook so that you can readily relate your observations to a definite locality.

Next, look over the entire outcrop from a distance in order to see major features. At a road cut, stand across the road and observe the outcrop. Describe important observed features like the following carefully in your notebook and sketch the outcrop, marking specially interesting things you notice. If you have a camera, photograph the outcrop.

Layering—Does the outcrop contain distinct layers or does it appear massive and unlayered? If layered, what distinguishes the different layers—a difference in color, size of grains, kind of vegetation that grows on various parts of the rock? (See *Field Guide to Layered Rocks*, in References.)

Folding—Are the layers horizontal or tilted? If tilted, in which direction and how many degrees from horizontal? Are there obvious folds in the layers? If so, describe them. (Appendix V describes ways of measuring the tilt of the layers.)

Intrusions—Do intrusions cut across the layering or across the parallel arrangement of minerals in the rocks? Are mixed rocks present?

Breakage patterns—Do the rocks break into blocks or split readily into platy fragments?

Weathering—Are the rocks weathered or fresh? (See *Field Guide to Rock Weathering*, in References.) Before moving up to the outcrop, view it from several places. Any outcrop presents a problem in solid geometry, and you may see relationships on one surface that do not appear on another. In Figure 9, for example, the surface labeled "A" suggests a uniform and unlayered rock. The surface labeled "B", however, reveals that the rock is actually layered.

Now move close to the outcrop. Do you observe layering that was not obvious from your overview? Describe the texture of the rock, how the individual mineral grains fit together. Are individual mineral grains within the rock flat and parallel like sheets in a pad of paper? If so, the rock texture is *foliated*. Are elongated mineral grains aligned parallel to each other like pencils in a bundle? If so, the texture is *lineated*. Do the minerals define more or less parallel planes? Are these planes horizontal, vertical, or tilted?

Break off pieces of rock from various layers or parts of the outcrop. On your sketch of the outcrop, number the locations of rocks examined.

Figure 9. Sketch of an outcrop. A, the weathered, massive-looking surface. B, a side view that reveals layering.

Use your hand lens and the mineral identification key (Appendix I) to identify the various minerals. Estimate the relative amounts of the different minerals, using the percentage estimation key in Appendix III. Then name the rock using the rock identification key in Appendix II.

Label samples of various rock types, keying them to your sketch of the outcrop. You can study these samples more carefully at home. Use Appendix II or IV to identify the likely parent rocks of various metamorphic rock types you sampled.

Visit other nearby outcrops. How do they resemble or differ from the first outcrop?

Activities for Areas Without Suitable Outcrops

In areas north of the limit of the Pleistocene ice sheet (shown in Figure 8), you may find boulders of metamorphic and plutonic rocks even though no nearby outcrops occur. Go to a field containing boulders or to boulders piled along a fence. How much information can you gain from observing single boulders? How many different kinds of rock can you find?

If possible, find gravel exposed in a road cut, gravel pit, or stream bank. Collect 100 pebbles and boulders; do not choose special ones, but take all pebbles and boulders within a small area until you have 100. Use the rock identification chart (Appendix II) to identify the rock types.

What percentage of the pebbles is plutonic? What percentage is metamorphic? What percentage is neither plutonic nor metamorphic? What is the nearest source of the plutonic and metamorphic material? How many different types of plutonic and metamorphic rocks do you find?

Pebble counts will force you to look carefully at the rock fragments of a gravel bed. Geologists who study glacial deposits commonly make pebble counts and from them recognize deposits from various sources and of different ages.

Another good place to observe plutonic and metamorphic rocks is in cemeteries. Just remember not to use hammers. How many different rock types do you observe in a cemetery? Is there a difference in rock type between older and newer tombstones? Which have been least durable? Why? (For further suggested activities, see *Field Guide to Rock Weathering*, in References.)

How many different plutonic and metamorphic rocks can you find that have been used as building stone or in sidewalks and curbstones? Do you find a higher percentage of plutonic and metamorphic rocks or of sedimentary and volcanic rocks? Do you find that specific rock types are used for special purposes? Try to discover a reason for what you observe.

Many museums contain displays of rocks and minerals. Visit displays in nearby college or university geology departments, state geological survey offices, or mining company offices. Compare your samples with the display specimens to verify your identifications. If you do not agree with the museum's identification, do not hesitate to challenge it.

ADVANCED FIELD PROJECTS

A single outcrop is like one piece of a jigsaw puzzle. You will get more satisfaction from putting the puzzle together than from looking at a single piece. Observing single outcrops, identifying rocks, and making collections are interesting activities in themselves, but by themselves they rarely lead to solutions to bigger problems. To develop a regional geologic history or an understanding of major processes operating below the surface, examine several outcrops and relate your observations from one outcrop to the next.

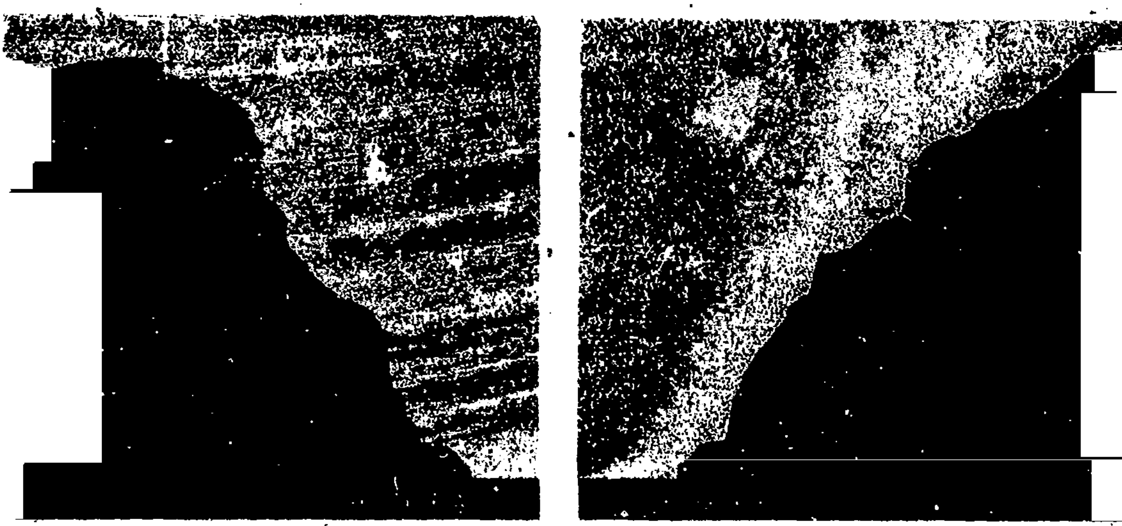


Figure 10. Views of two adjacent outcrops. Note how it appears that the layers can be matched up even though they are not in contact.

Describing a Section

In layered rocks, measure the thickness of distinct layers in several nearby outcrops (Figure 10). Using notebook sketches, arrange the layers from each outcrop in their proper sequence. If several outcrops contain layers of marble, for example, are they of the same thickness at each outcrop? Can the rock types above and below a marble layer in one outcrop be found in the same relative positions in other outcrops? Does a distinctive rock type, such as amphibolite or quartzite (see Appendix II for description), characterize a certain level in the sequence of layers? Use the measurements and rock descriptions from several outcrops to relate outcrops to each other. The process of comparing related layered sections from different places is called *matching* or *correlating*. (See *Field Guide to Layered Rocks*, in References.) Try to build a composite sequence of layers for a whole area.

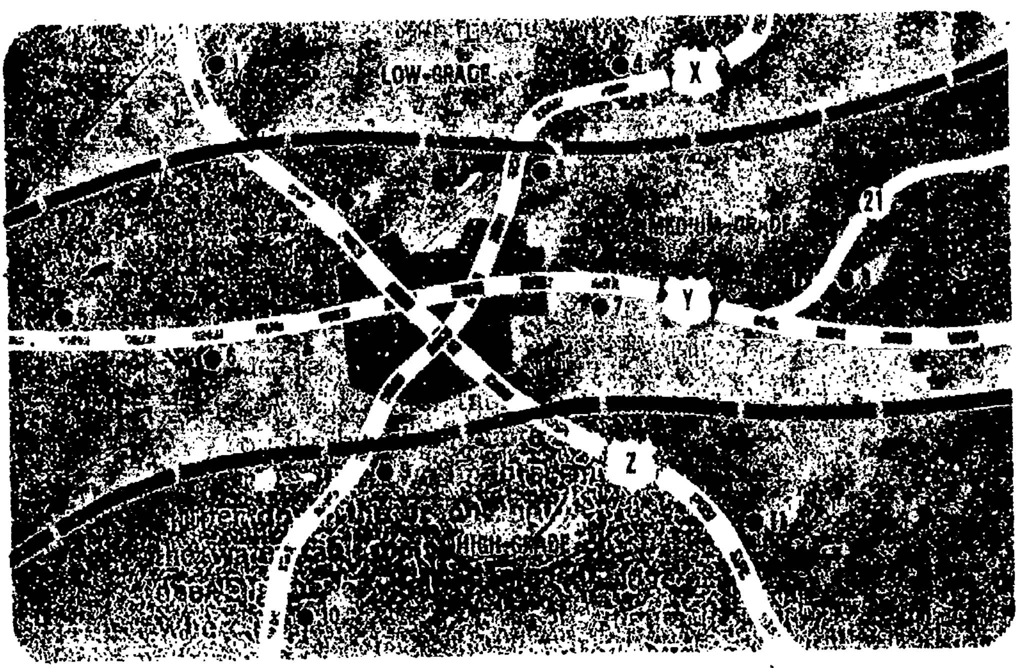
Once you have determined the relative positions of various distinctive rock types in a sequence of layers, study the minerals in each layer and attempt to determine the parent rocks. For example, suppose that in several outcrops you find an easily recognizable sequence of layers including a layer of marble, a layer of quartz-mica schist, and a

The dashed lines in Figure 11 separate areas containing mineral assemblages of different grades. These dashed lines separating rocks of different grades are called *isograds*, lines of equal grades or amounts of metamorphism.

With this information you can make inferences about the rocks you are studying. Then you can begin to answer the following questions:

1) What rocks probably existed in the area before metamorphism? *Possible answer:* shaly and limy sedimentary rocks.
2) How deeply were these rocks buried? To what maximum temperatures were they subjected? *Possible answer:* From Figure 5 you can infer that the low-grade rocks have probably been buried at least 15 kilometers deep and have been subjected to temperatures above 350°C.
3) Which part of the area was once subjected to the highest temperatures and pressures, and was thus probably most deeply buried? *Possible answer:* The southern part, because

Figure 11: Constructing a map to show changes in metamorphic grade. Light lines represent roads; dark lines represent boundaries between areas of equal metamorphic grade (Appendix IV); numbered dots represent sample-collecting points.



layer of quartzite. What parent rocks do these three rock types imply? From Appendix II you might infer that this was probably a sequence of limestone, shale, and sandstone.

The Grade of Metamorphism

Collect several samples from outcrops of metamorphic rocks. Using Appendices I and II, identify the minerals present. Pay special attention to the groups of minerals that are found together in a single rock type. Consult Appendix IV to attempt to determine the grade or degree of metamorphism and the parent rocks of each group of minerals. (*Note*: The tables presented in this pamphlet are simplified. More detailed tables are found in some of the sources in the References.)

How many different parent rocks are represented? Plot your data on a map like that in Figure 11. Note that stations 1 and 4 of this figure contain *mineral assemblages*, series of minerals closely associated within a single rock type, common in low-grade metamorphic rocks. Assemblage 1 is muscovite-chlorite-quartz-plagioclase; assemblage 2 is calcite-dolomite-quartz. Appendix IV indicates that these are low-grade metamorphic rocks.

At stations 2, 3, 5, 6, 7, and 8, assemblage 1 is kyanite - garnet - muscovite - biotite - quartz; assemblage 2 is calcite-pyroxene-deep red garnet. According to Appendix IV these are medium-grade metamorphic rocks.

At stations 9, 10, and 11, assemblage 1 is sillimanite - garnet - potassium feldspar - plagioclase - quartz; assemblage 2 is plagioclase-pyroxene. These assemblages indicate high-grade metamorphic rocks (Appendix IV).

Assemblage 1 for each zone was seen in rocks probably derived from shaly parent rocks. Assemblage 2 for each zone was seen in rocks probably derived from limy parent rocks. The conclusions on parent rocks are also based on Appendix IV.

it contains higher-grade metamorphic rocks. Note that if a granite pluton were found just south of the map area, heat and hot liquid from the cooling pluton might have influenced the metamorphism.

Special Features of Plutons

In plutonic rocks, look for all contacts of different rock types. The surface or zone where the plutonic rock meets surrounding rocks is an important contact. Commonly, metamorphic rocks surround plutons, but some plutons are in contact with sedimentary rocks, volcanic rocks, or other plutonic rocks. Careful observation of the outer contacts of plutons may suggest whether the pluton is older or younger than adjacent rocks.

If fragments of the surrounding rock appear to have fallen into the pluton, if intrusions can be traced outward from the pluton into adjacent rocks, and if the rocks surrounding the pluton were baked by contact metamorphism, the pluton is younger than the rocks surrounding it. If, on the other hand, fragments of the plutonic rock occur in the overlying rocks, the pluton is probably older, and the surrounding rocks were deposited later on top of the pluton.

Some plutonic rock masses are nearly uniform in composition. You may be able to examine this rock for kilometers without seeing much change in rock type or structure. Other plutons are made up of several rock types. Contacts between the various types may be sharp or gradational. Watch carefully for changes in color or structure of the rock.

Although plutonic rocks, and some metamorphic rocks, may appear uniform over wide areas, subtle zoning and slight changes in rock type may occur. To determine the nature of such variations, collect samples at regular intervals. Set up a grid pattern

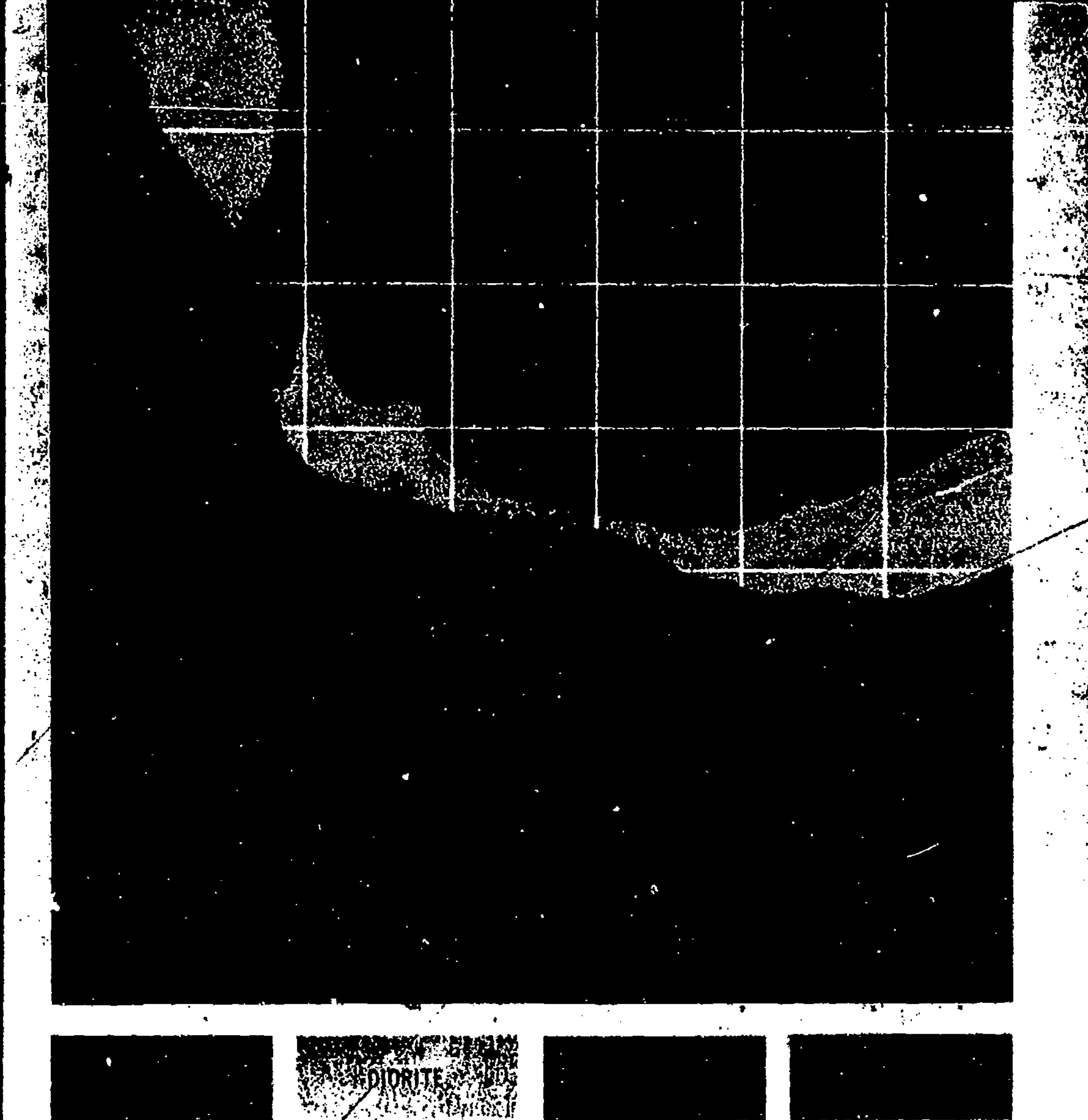


Figure 12. Sample of a geologic map from an area of igneous and metamorphic rocks. Contour lines are not shown. In the field you would use them to locate stations and to draw contacts between rock types. The granite is homogeneous and a sampling grid has been ruled on it.

on your map (Figure 12), dividing the map into squares, perhaps half a kilometer on each side. Collect a sample at each corner of the grid squares. At home, place all the samples in their proper relative positions. Do you detect differences which casual observation did not disclose? Are rocks in one part of the pluton slightly darker in color, do they contain grains of a different size, or do they contain greater amounts of a particular mineral such as quartz or potassium feldspar? Once you discover subtle variations, you can develop an eye for recognizing them in the field.

Mapping Metamorphic and Plutonic Rocks

To make a more complete field study, prepare a geologic map. First develop skill in identifying rocks, locating your position on the map, and making basic observations at individual outcrops. A geologic map shows in detail where various rock types are located and indicates their structure. Think of the map as what you would see if you photographed a three-dimensional model of the area.

First you need a base map of the study area. If a topographic map is not available, a road map may do. The more detailed you want the geologic map to be, the better and more detailed the base map must be. Information is then plotted on this map.

A geologic map of an area of metamorphic and plutonic rocks in northern California is shown in Figure 12. The process was begun by first examining individual outcrops. At stations 1 and 2 the mapper found diorite, a plutonic rock described in Appendix II, and at stations 3 and 4 he found hornblende schist or amphibolite. Having established the rock types of these four stations, he then drew a contact line on the map. This line represents the outcrop of the zone that separates diorite from hornblende schist. North of this contact, until granite appears, the rock is diorite; to the south, until quartz-mica schist appears, it is hornblende schist. The mapper continued to make new observations and record them on the map until he had outlined the boundaries of rock units he could recognize. If contacts are traced carefully, they may outline major structural features as well as rock types. Note the folds in the lower half of Figure 12 and try to visualize them in three dimensions.

Observe the direction and inclination from the horizontal of layered rocks shown by appropriate symbols on the map (stations 3 and 4, Figure 12). The longer line, called the *strike line*, represents the direction you would read from a compass if you sighted the compass along a horizontal line drawn on the surface of the layers. This line actually has two possible directions: the words *east* and *west* merely describe opposite ends of the same lines. The triangle or short line points in the direction a drop of water would roll down the sloping surface of a single layer; the number shows the *dip*, the angle of inclination in degrees from the horizontal. Appendix V describes how to measure strike and dip.

A possible detailed set of field notes for the map in Figure 12 is shown in Figure 13.

While working in the field, think of several possible ways to explain the features you observe. In the example of Figure 12, the rock at station 3 was described as metamorphic and the rock at station 1 as plutonic. Somewhere between the two stations there must be a contact between the two rock types. Four hypotheses should be considered, and others could be proposed:

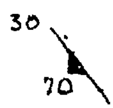
1) The diorite may be older than adjacent rocks and may represent a platform on which the latter were deposited.
2) The diorite may be younger, and therefore intrusive into the older metamorphic rocks.
3) The diorite may be the same age as the surrounding rocks, but "granitized."
4) A fault may exist between the diorite and the adjacent rocks which makes it difficult to tell the age relationships.

Every bit of evidence bearing on the problem should be examined to determine which explanations it supports or contradicts. For example, the presence of diorite dikes cutting across the metamorphic rocks favors the second explanation. Examine each bit of new data in this way. Sifting several pieces of evidence may make it clear that the second hypothesis is most reasonable. However, a better hypothesis than the ones previously considered may be developed later on.

J. Johnson July 24, 1971

Map Sheet: Etna quadrangle, 15 minute series, U.S. Geol. Survey

Station #	Attitude	Description and Remarks
1 (top of ridge)	no foliation seen	Outcrop 7.5 m. long 3m. high, flat cliff face. Rock fresh looking except for upper ½ meter which is crumbly. No layers or foliation : Very homogeneous Rock Description: granular fabric grain size 2-4 mm. Quartz absent. Plagioclase feldspar 65% Biotite 10% Hornblende 25% Rock Name: Diorite
3 (down on side of hill)	foliation: strike: N. 30° W. Dip: 70° SW	Low outcrop 30 cm. high. Greenish gray on weathered surface, black where fresh. Rock Description: lineated, average grain size 1-3 mm. Hornblende 60% Plagioclase 35% Garnet 5% Garnet Amphibolite (or Hornblende Plagioclase Garnet Schist)



Note: Contact between Diorite and Amphibolite is between stations 1 and 3. Not exposed so I don't know yet what relationship is between the two.

If you plan to prepare a geologic map, consult geologists who may live nearby. College, university, and state geological survey geologists will be happy to discuss geology and maps with you.

Figure 13. Sample page from field notebook recording typical field description of geologic relationships in Figure 12.

Cross-Country Geology

When you take weekend trips or vacations, carry a road map and note the location and types of metamorphic and plutonic rocks you observe. Order a copy of the state geologic map by writing to the state geological survey. For cross-country trips, carry a set of the geological highway maps of the states you will cross. (See References.) Follow your route on these geologic maps and keep a notebook of your roadside observations.

Figure 14. How to use a hand lens. Hold the specimen a few centimeters away from the eye and in good light. Study at least three surfaces of the specimen at nearly right angles to each other.

APPENDICES

I—Key to Rock-Forming Minerals

To use the table, apply all tests described to individual mineral grains and not to the whole rock. Use a hand lens (10- to 20-power). The technique for using a lens is shown in Figure 14.

If the mineral is colored, first look in the sections of the table referring to colored minerals. If you cannot make a satisfactory identification, try the section dealing with colorless, white, or light-colored minerals.

Describe the cleavage of the mineral. *Cleavage* is the tendency of a mineral to split along closely-spaced, flat surfaces. Some minerals have several different directions of cleavage. For example, when you break a crystal of *halite*, common table salt, it will split into small fragments that have right angles between all flat surfaces. Use your hand lens to examine some common table salt. Halite has three directions of cleavage. Some minerals have no cleavage. Instead, they break along irregular surfaces. Quartz, for example, breaks the way glass does. It has a *conchoidal* or shell-like fracture.

Determine the hardness of the mineral. Can you scratch it with your fingernail, a penny, or a pocket knife? If it is harder than a knife blade, consider it hard.

In using the table,

1) First look up the proper color in column 1.
2) Within the proper color group in column 2, locate the compartment containing minerals with the right cleavage.
3) In column 3, within the same cleavage compartment, find minerals of the same hardness.
4) Then examine any special properties until you locate a mineral name in the last column.

For an identification to be correct, the mineral name you choose must fit all properties directly to its left in columns 4, 3, 2, and 1. For example, suppose you find a green mineral with good cleavage. The mineral cannot be scratched with a knife. Upon close examination you find that it has two cleavage directions at about right angles to each other. The name of the mineral, according to this table, is potassium feldspar.

What do you do if you can't decide on the proper name?

1) Take a sample of the rock containing the mineral and determine what it might be by comparing it with display specimens in a museum.
2) Try using tables from a more detailed mineralogy book. (See References.) You may have found a mineral that is not included in Appendix I.
3) If you still cannot identify the mineral, ask a geologist or earth science instructor for help. Sometimes geologists have to examine minerals under a microscope, applying various special tests. They may even need X-ray studies to identify the mineral.

(*Note*: Some mi[illegible]ls appear in more than one section of the tabl[illegible] because they may vary in color or other properties.)

Color	Cleavage	Hardness	Other Distinguishing Characteristics	Name
red or brown	good cleavage	can be scratched by penny or easily by knife	splits into thin sheets (1 perfect cleavage) which are nearly transparent, bend easily, and snap back; usually dark brown or black	BIOTITE MICA
	no good cleavage	cannot be scratched by knife	commonly well-formed crystals grow together to form a cross; usually rather dull	STAUROLITE
			almost spherical, 12-sided crystals when well formed; glassy looking; also may be green, white, black	GARNET
			stubby, square crystals; commonly has black inclusions in shape of a cross; when altered it may be softer than a knife; red, brown, or olive green	ANDALUSITE
			conchoidal fracture; glassy; small stubby grains; common in marble; in other rocks generally green or yellow	OLIVINE
blue	good cleavage	can be scratched by knife but not by penny	long, flat crystals can be scratched by knife parallel to the long direction, but not parallel to the width; pale blue but may also be colorless	KYANITE
pale ...rs see also "colorless, etc.")	moderate cleavage	cannot be scratched by knife	cleavage may be poor; various shades of blue; glassy looking	CORDIERITE

green or black (for pale colors see also "colorless, etc.")	good cleavage	can be scratched by fingernail	1 perfect cleavage; splits into pearly sheets that bend but do not snap back	CHLORITE
		can be scratched by penny but not by fingernail	black; 1 perfect cleavage; splits into sheets that bend and snap back	BIOTITE MICA
		about same hardness as knife; mineral and knife will probably scratch each other	2 good cleavages; cleavage planes form 120° angle; crystals usually longer than they are wide; usually dark but some rarer varieties are pale green, white, blue, or brown	HORNBLENDE (AMPHIBOLE)
			2 good cleavages; cleavage planes form 90° angle; crystals usually stubby	PYROXENE
		cannot be scratched by knife	2 good cleavages at almost 90° angle; usually white or pink, occasionally bright green	POTASSIUM FELDSPAR
			1 perfect cleavage, 1 poor cleavage; glassy looking; usually pistachio-green	EPIDOTE
	no good cleavage	cannot be scratched by knife	almost spherical 12-sided crystals when well formed; more commonly red or brown	GARNET
			stubby, square crystals; commonly has black inclusions in shape of a cross; when altered it is softer than a knife.	ANDALUSITE
			conchoidal fracture; glassy; small, stubby grains; green and yellowish varieties common in gabbros.	OLIVINE

Color	Cleavage	Hardness	Other Distinguishing Characteristics	Name
colorless, white, or light colored	good cleavage	can be scratched by penny	white, pearly, or transparent; splits into thin transparent sheets which bend easily and snap back; 1 perfect cleavage; flat, hexagonal crystals occasionally found	MUSCOVITE MICA
			3 good cleavages; mineral breaks into perfect rhomb-shaped fragments; fizzes when hydrochloric acid is dropped on it; usually white or colorless; may also be tinted gray, green, blue, yellow, pink	CALCITE
		cannot be scratched by penny but can be scratched by knife	easily scratched with knife; 3 good cleavages; breaks into perfect rhomb-shaped fragments; large pieces will not fizz in cold hydrochloric acid, but a powder of the mineral will fizz in acid; hot acid will also cause mineral to fizz; commonly pale pink, but may be colorless, white, gray, green, brown, or black	DOLOMITE
			long, flat crystals can be scratched by a knife parallel to the long direction of crystal, but not parallel to the width; pale blue or colorless	KYANITE

colorless, white, or light colored (cont.)	good cleavage (cont.)	cannot be scratched by knife	common rock-forming mineral; 2 good cleavages at nearly right angles; roughly rectangular, blocky crystals; narrower edges contain parallel striations that look like deep scratches (usually seen only under hand lens); usually white or clear; may be gray, dull green, yellow, or pink	PLAGIOCLASE FELDSPAR (SODIUM-CALCIUM FELDSPAR)
			common rock-forming mineral; 2 good cleavages at about right angles; roughly rectangular, blocky crystals; distinguished from plagioclase by lack of striations; usually pink or white; occasionally colorless or bright green	POTASSIUM FELDSPAR
			1 good cleavage; long slender crystals; may be white, pale brown, pale green	SILLIMANITE
	no good cleavage	cannot be scratched by knife	1 poor cleavage; various shades of blue	CORDIERITE
			almost spherical, 12-sided crystals when well formed; may be white or pale pink; usually darker red, brown, or green	GARNET
			one of the most common rock-forming minerals; conchoidal fracture; well-formed crystals usually pointed, hexagonal; usually white, colorless, or pale gray; some varieties pink, darker gray, violet, brown, or pale blue	QUARTZ

II—Identification of Metamorphic and Plutonic Rocks

The following terms are useful in describing the texture of metamorphic and plutonic rocks. *Texture* is the way the grains fit together.

Schistose or foliated—Rocks that split easily into platy fragments. The terms *schistosity* and *foliation* refer to sheetlike layering of mineral grains. Rocks that show this feature generally contain flakes of mica or other flat minerals arranged in parallel sheets (Figure 3). Depending on the size of the grains, rocks with schistose textures are given specific names.

1) *Slate* is so fine-grained that individual mineral grains cannot be seen, even with a hand lens. It splits easily into hard, flat plates that are commonly used as roofing tiles and chalk boards. Slate has a dull luster.
2) *Phyllite* has slightly larger mineral grains than slate. Tiny mica flakes may be seen on the flat rock surfaces. Because of the coarser crystals, phyllite has a shinier appearance along the surface of splitting than slate.
3) *Schist* contains grains large enough to be easily seen with the naked eye.

Lineated—Rocks consisting of elongated, pencil-shaped minerals with their long dimensions oriented parallel to each other.

Granular—Mineral grains that look square, rectangular, or round under the hand lens. Mica flakes or elongated minerals may be present, but they are not arranged in parallel fashion. Granular rocks do not split into thin platy fragments the way schists do. Most plutonic and some metamorphic rocks have granular textures (Figures 1 and 3C).

When examined carefully under a hand lens or microscope, almost all metamorphic and plutonic rocks reveal completely interlocking grains with no open spaces between them.

To use the table, first identify the texture of the rock from the foregoing descriptions. Then identify the minerals present and estimate their relative percentages and grain size. With these data, move across the table from the left-hand column to the proper name at the right. Add the names of the most abundant minerals to give a complete rock name. A schist with 45 percent quartz, 35 percent muscovite mica, and 20 percent garnet is called a quartz-muscovite-garnet schist.

The rocks from slate through gneiss are metamorphic. Those from granite down the column are plutonic. However, some gneisses grade into plutonic rocks, and some granites may be metamorphic. In doubtful cases such names as "granite gneiss" or "gneissic granite" may be used.

In order to give plutonic rocks more complete names, add the names of abundant minor minerals (excluding the essential ones). For example, a granite containing 30 percent quartz, 40 percent potassium feldspar, 15 percent plagioclase feldspar, 10 percent muscovite mica, and 5 percent biotite mica should be called a muscovite-biotite granite, since the word granite already includes the quartz, potassium feldspar, and plagioclase.

(*Note*: This table presents a simplified field classification. In order to assign more precise names, see References.)

Texture	Grain Size	Essential Minerals	Name	Probable Parent Rock
	fine-grained=less than 1 mm medium-grained=1–5 mm coarse-grained=more than 5 mm			
foliated (schistose)	grains too fine to be seen with hand lens. shiny surface	none—the name "slate" relates only to texture	SLATE	shale
	grains large enough to be seen with hand lens	none—name relates only to texture	PHYLLITE	shale
	virtually all minerals large enough to be seen easily; rock flaky	none—name relates only to texture	SCHIST	shale volcanic rock shaly sandstone
	usually fine-grained and roughly foliated but may be granular; green to black in color; greasy looking	serpentine minerals (chlorite and fibrous minerals like asbestos)	SERPENTINITE	peridotite or pyroxenite (see below)
lineated (elongated	medium- to coarse-grained	usually amphibole and plagioclase	AMPHIBOLITE	volcanic rock or impure limestone

Texture	Grain Size	Essential Minerals	Name	Probable Parent Rock
granular, usually layered or streaky looking	very fine-grained; may have some large, well-formed crystals surrounded by fine-grained material; commonly flinty looking	none-name relates only to texture	HORNFELS	can be anything
	fine- to medium-grained	mostly quartz (rock very hard; gray or white, sometimes red)	QUARTZITE	sandstone
	fine to coarse	calcite or dolomite (rock soft; usually reacts with HCl)	MARBLE	limestone
	medium to coarse	commonly contains quartz, feldspar, and dark minerals	GNEISS	feldspar-rich sandstone, granite
granular, unfoliated or only slightly foliated	medium to coarse	quartz, potassium feldspar, plagioclase	GRANITE	crustal rock has probably been melted or granitized

granular, unfoliated or only slightly foliated (cont.)	medium to coarse (cont.)	quartz absent, plagioclase, dark minerals less than 50%	DIORITE	from a melt?
		quartz absent, plagioclase, dark minerals more than 50%	GABBRO	melt from sub-crustal or lower crustal rocks?
		quartz absent, potassium feldspar	SYENITE	from crustal rocks?
		quartz absent, feldspar absent, dark minerals only	PERIDOTITE (predominantly olivine)	sub-crustal rocks?
			PYROXENITE (predominantly pyroxene)	sub-crustal rocks?
			HORN-BLENDITE (predominantly hornblende or other amphibole)	sub-crustal or crustal rocks?
	very coarse; some very large, well-formed crystals; occurs usually as intrusions or pods		PEGMATITE (depending on minerals present call these granite-gabbro pegmatite, etc.)	melt from crustal or sub-crustal rocks

III—Percentage Composition of Rocks

To use the charts (Figure 15), assume, for example, that you wish to estimate the total percentage of dark minerals present in a rock. First look carefully with either your naked eye or a hand lens at the hand specimen of the rock. Note the distribution ratio of dark-colored minerals to light-colored minerals. Then compare this sample with the charts. Try to make accurate estimates for all major minerals you have distinguished. With practice, you can develop an accuracy within about five to ten percent.

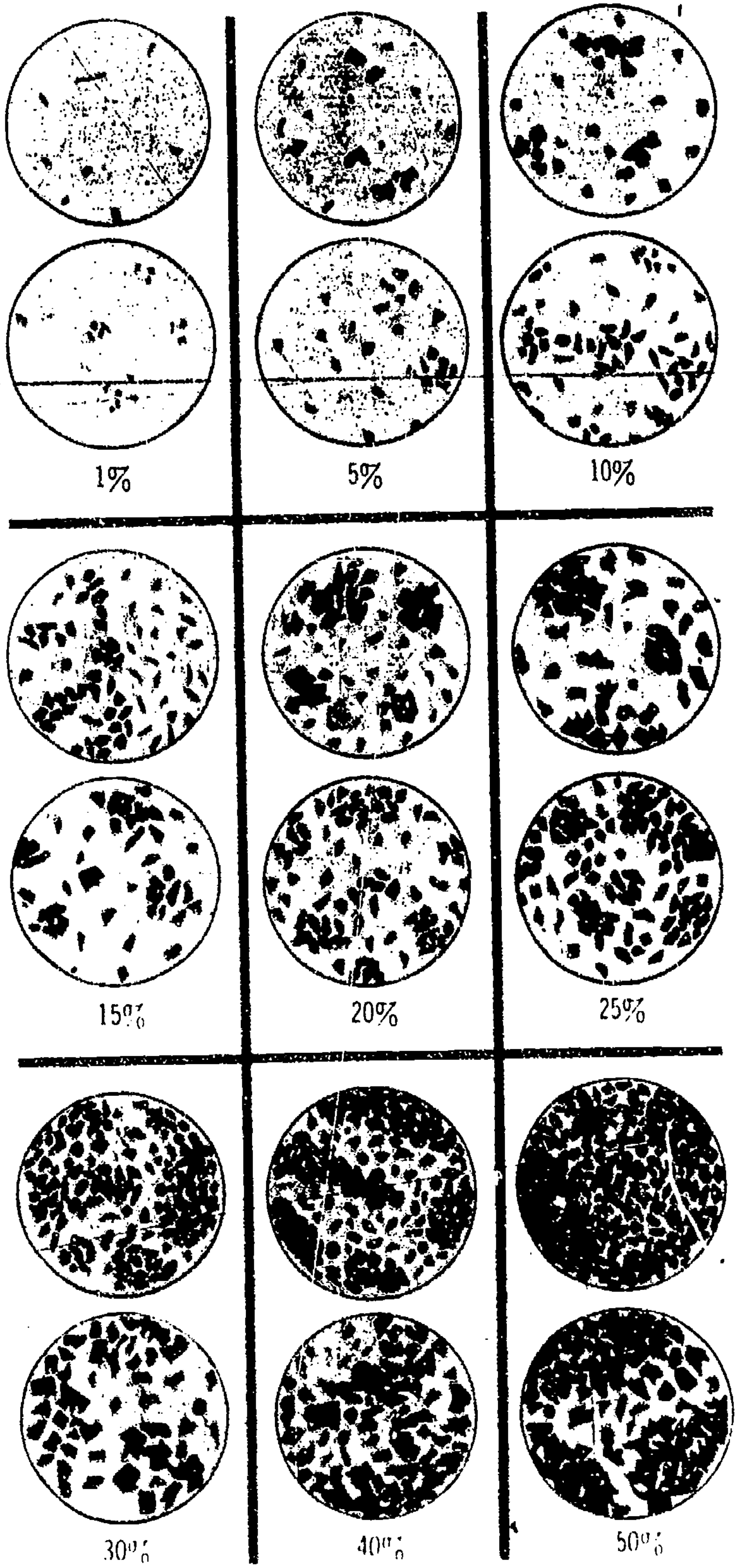


Figure 15. Charts to assist you in estimating percentages. Note the difference in appearance between a few large dark areas and many small dark areas.

IV—Typical Mineral Assemblages and Probable Parent Rocks

(*Note*: More complete lists can be found in *Petrography* or in other college petrology textbooks. See References.)

Metamorphic Grade	Shaly or Clayey Parent Rocks	Parent Rocks Rich in Quartz and Feldspar (Sandstone, Granite, Volcanic Rocks)	Limy Parent Rocks (Limestone, Dolomite)	Iron- and Magnesium-rich Parent Rocks (Gabbro, Basalt)
Low-pressure Metamorphism by Baking	muscovite-biotite-quartz-andalusite andalusite-cordierite-potassium feldspar-quartz	quartz-potassium feldspar-plagioclase-biotite	calcite-garnet-pyroxene, and other calcium-bearing minerals (garnet usually red-brown or pale green)	plagioclase-hornblende-pyroxene
Low-grade	muscovite-chlorite-quartz-plagioclase (sodium-rich) biotite-muscovite-quartz-sodic plagioclase	quartz-sodic plagioclase-epidote-(muscovite) quartz-sodic plagioclase-epidote	calcite-dolomite-quartz calcite-amphibole-epidote-quartz	sodic plagioclase-chlorite-calcite sodic plagioclase-chlorite-amphibole-epidote

Medium-grade	garnet-biotite-muscovite-quartz-sodium-calcium plagioclase kyanite-garnet-muscovite-biotite-quartz staurolite-garnet-biotite-muscovite-quartz sillimanite-biotite-muscovite-garnet-quartz	quartz-potassium feldspar-sodium-calcium plagioclase-biotite-muscovite	calcite-pyroxene-quartz calcite-pyroxene-garnet (garnet usually deep red)	hornblende-sodium-calcium plagioclase-epidote-quartz-biotite hornblende-sodium-calcium plagioclase-garnet
High-grade	sillimanite-(kyanite)-garnet-potassium feldspar-plagioclase-quartz	quartz-potassium feldspar-plagioclase-sillimanite-garnet quartz-potassium feldspar-plagioclase-pyroxene-garnet	calcite-pyroxene-quartz-plagioclase plagioclase-pyroxene	plagioclase-pyroxene-garnet olivine-pyroxene-amphibole
Very high-grade	—	—	—	green pyroxene-garnet

V—Making Measurements on Tilted Rocks

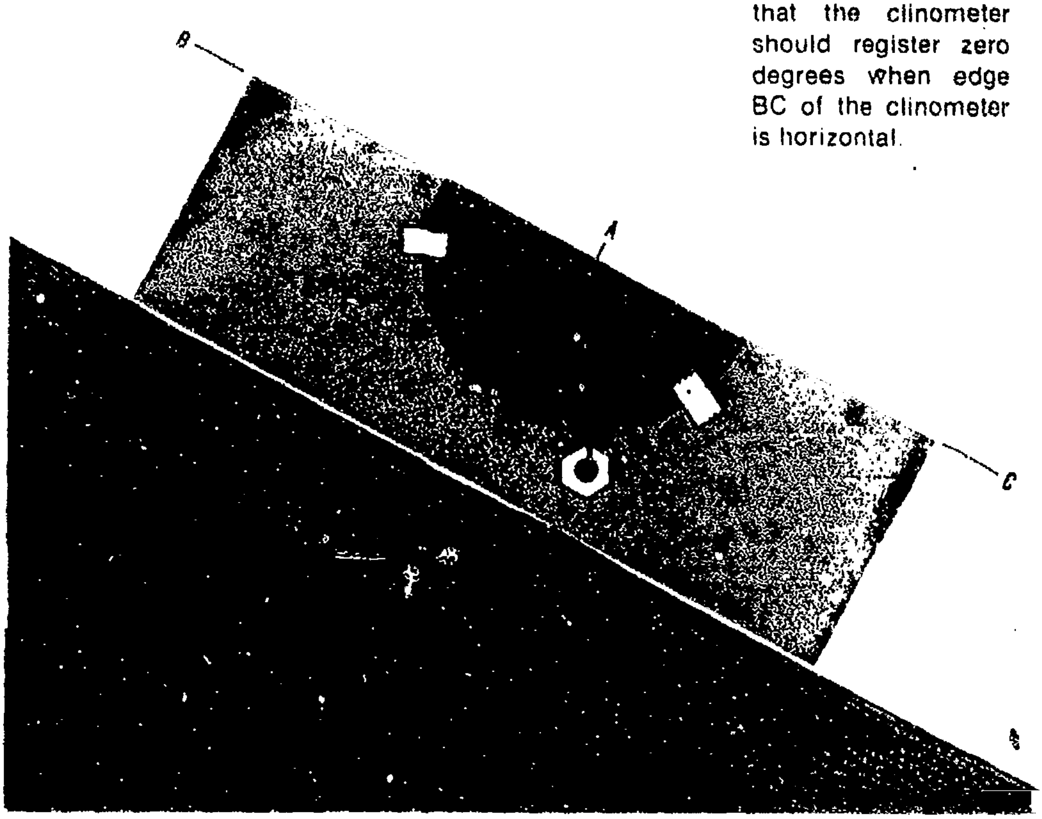
Figure 16 shows what strike and dip are. To measure the strike, place a clinometer (Figure 17) on the top of a layer. Be sure to measure the actual top of a single layer, or the foliation plane, and not merely the rounded top of an outcrop. Move the clinometer until it reads zero degrees. Draw a line along the flat surface of the rock layer parallel to the edge of the clinometer. This is a horizontal line on the surface of the layer and is therefore the *strike line* of the layer. Could you measure the strike of a horizontal layer? Why? Measure the compass bearing of the strike line you have drawn on top of the layer, and record this figure as the direction of strike.

Figure 16. Strike and dip of tilted layers.

In order to measure the dip of the layer, put the clinometer at a right angle to the strike line (Figures 16 and 17). Read the *dip angle* directly from the clinometer and record it in your notebook. The *dip* is actually the maximum angle of tilt of the layer measured from the horizontal, so you can also measure it by simply moving the clinometer around on the surface of a layer until you reach the maximum possible angle for the given surface.

Why measure strike and dip? Strike and dip symbols on a map help you remember how the layers slant into the ground. Furthermore, from such measurements you can project the position of the layers underground and make inferences about their shapes.

Figure 17. Construction of a simple clinometer: Tape a protractor onto a piece of stiff cardboard or plywood as shown. Drill a hole through point A and attach a piece of string. Weight the string with a piece of metal. Place the clinometer on any inclined surface as shown and read the angle. Note that the clinometer should register zero degrees when edge BC of the clinometer is horizontal.



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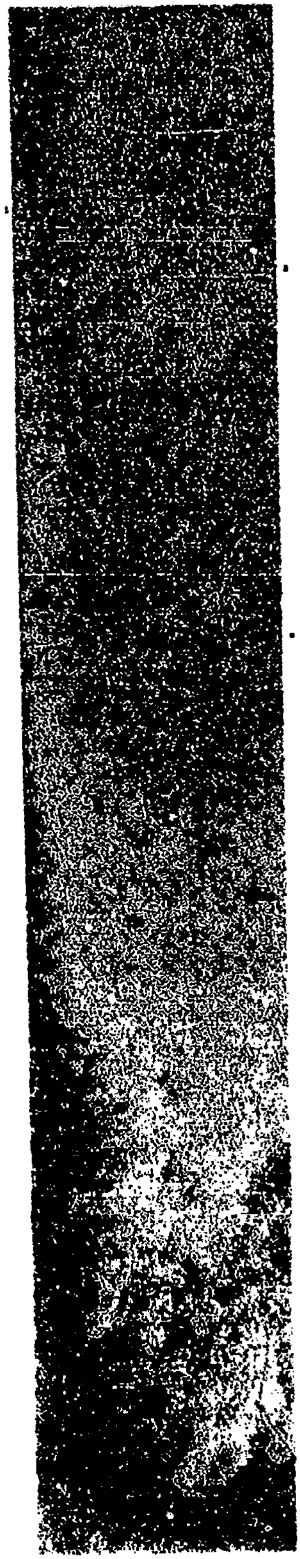

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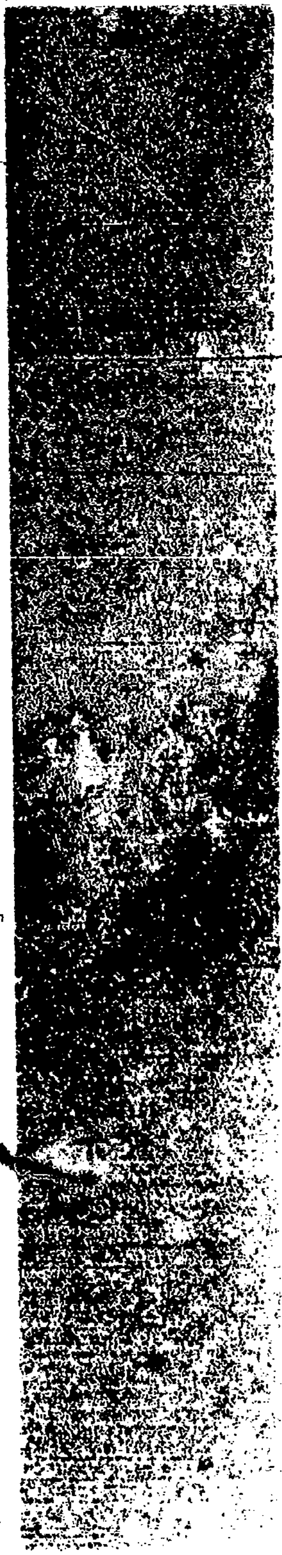


Glossary

clinometer—a device for measuring the tilt of rock layers.

contact metamorphism—chemical changes without melting in minerals, and changes in their arrangement in a rock. It is caused by exposure of a rock to great heat, as when molten rock intrudes another rock.

crystalline texture—an arrangement of the mineral grains forming a rock in which the edges of grains are tightly interlocking, with no free spaces between them. This texture is found in most plutonic and metamorphic rocks; it is also found in some sedimentary rocks, as in some limestones.

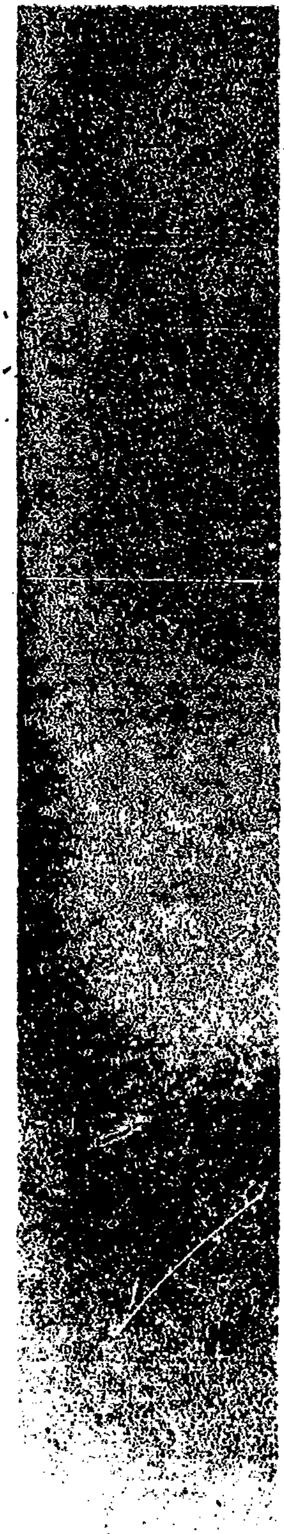
dip—the angle at which a rock layer is tilted into the ground, measured from the horizontal and at a right angle to the strike.

foliated texture (schistose)—having flat mineral grains that lie parallel to each other like sheets in a pad of paper.

granitization—formation of granite from other rock types several kilometers below the earth's surface in environments where temperature and pressure are high enough to allow chemical elements to move about without actual melting of the rock.

igneous rock—rock that crystallized from molten rock liquid or magma.

intrusion—a body of rock that has been injected or has oozed into other rocks. Many intrusions are thought to have occurred when the intruding rock was molten. "Solid" rock can



also become relatively plastic or doughy and be intruded.

isograd—a line drawn on a map, separating rocks which have undergone different amounts of metamorphism and are of different metamorphic grade.

lineated texture—having elongated mineral grains arranged parallel to each other like a bundle of pencils.

magma—melted rock.

metamorphic grade—an index describing how much a metamorphic rock differs from the rock it came from. For example, high-grade metamorphic rock is rock that has been subjected to high temperature and pressure.

metamorphic rock—rock that has formed under conditions of high temperature and pressure generally several kilometers below the earth's surface, having an interlocking arrangement of mineral grains known as crystalline texture. Chemical rearrangements and changes in shapes of mineral grains have occurred without actual melting of the rock from which they formed. Metamorphic rocks commonly have mineral grains arranged parallel to each other. Examples are slate, schist, and gneiss.

migmatite (mixed rock)—rock in which plutonic rock types and metamorphic rock types are mixed together in various ways.

mineral assemblage—the particular minerals that occur together in a given rock.

minerals—naturally occurring homogeneous solids which make up rocks.

parent rock—the rock from which a metamorphic rock is thought to have formed. For example, marble forms from the parent rock limestone, and quartzite forms from quartz sandstone.

pluton—a large body of plutonic rock, such as granite or gabbro, ranging in surface area from a few hundred square meters to many hundreds of square kilometers.

plutonic rock—normally coarse-grained rock that has crystallized deep below the earth's surface having an interlocking arrangement of mineral grains known as crystalline texture. Plutonic rocks are commonly of igneous origin, but may have formed without melting and therefore may actually be metamorphic rocks. Examples are granite and gabbro.

regional metamorphism—chemical changes without melting in minerals and changes in their arrangement in a rock; it occurs over a wide region and is generally related to folding and regional increases in temperature and pressure rather than the immediate proximity of a molten mass.

sedimentary rock—rock composed of particles of sand, clay, or other sediment, pressed or cemented together. Generally, sedimentary rocks are layered and their grains are arranged in a pattern with pore spaces between them.

strike line—a horizontal line drawn on a tilted layer.

PICTURE CREDITS

All photos are from the collection of the author, Dr. William D. Romey.

Pages 14-15, adapted from Robert R. Compton, *Manual of Field Geology*. New York, John Wiley & Sons, Inc., 1962.

Page 43, adapted from R. D. Terry and G. V. Chilfinger, *Journal of Sedimentary Petrology*, Volume 25, 1955.

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